Millisecond Pulse Generating System for a Continuous Wave CO$_2$ Laser
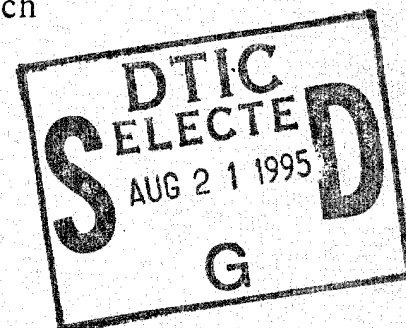
By

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13. ABSTRACT (*Maximum 200 words*)

A system has been developed for generating single millisecond pulses and pulse trains with a continuous wave industrial CO_2 laser while simultaneously measuring the corresponding irradiance with calorimeters that have a 0.5 s response time. First area moment equations are derived and used to balance the inertia forces of a continuously variable-angle chopper blade used in the system. The results of a study to determine calorimeter response time, investigate system accuracy, and demonstrate systems use are also presented.

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PREFACE

This report summarizes the design and use of a new system which has been developed for the production and measurement of CO_2 laser pulses in the millisecond range. This work is being done under the project <u>Thermal Protection</u>, 1L162786AH98CABOO, administered by the Technology Application Branch (TAB), Fiber and Polymer Science Division, Science and Technology Directorate, U.S. Army Natick Research, Development, and Engineering Center.

All experiments were performed at the Technology Application Branch, at the U.S. Army Natick Research, Development, and Engineering Center (Natick). The citation of trade names in this report does not constitute official endorsement or approval of use of an item.

MILLISECOND PULSE GENERATING SYSTEM
FOR A CONTINUOUS WAVE CO_2 LASER

INTRODUCTION

Thermal testing at the Science and Technology Directorate's Technology Application Branch (TAB) is currently being performed with an 820EP Spectra-Physics continuous wave CO_2 laser. The laser operates at a wavelength of 10.6 μm with a maximum output power of 2.5 kW. Single pulses are created via a water-cooled mechanical shutter located in the laser head. Experiments performed at the TAB[1] for the purpose of documenting the temporal characteristics of the shutter show that the minimum pulse width is about 100 ms. This study also shows that the open and close time of the shutter varies greatly. Though the average absolute deviation was 50 ms as stated by the manufacturer, random variations were observed ranging from 25 ms to 85 ms. These variations are substantial in the 100 ms range but become less so as the pulse width increases above 500 ms.

A mechanical variable frequency light chopper is available and has been used for the production of millisecond pulses. However, the calorimeters being used have a 0.5 s response time, and while it has been possible to create millisecond pulses, we have not been able to measure the corresponding irradiance.

In order to extend our pulse-creating capabilities into the millisecond range, a new system was developed that utilizes a set of two individually balanced blades, which can be set to create a continuously variable gap ranging from 0° to 170°. The problem of calorimeter response time is overcome by locating the chopper after the beam splitter (Fig. 1). This allows one to record the irradiance of the entire pulse emitted through the laser head shutter, at a location before that where the pulse is chopped. The period of rotation of the chopper is set equal to or greater than 500 ms -- the minimum pulse width that can be accurately measured by the calorimeter in the secondary beam. The variable gap is set to that angle, which will result in the desired pulse width at the target in the primary beam. This paper summarizes the design and application of the new system.

SYSTEM DESIGN

Design Considerations

The variable angle chopper blade was designed to be mounted on a commercial variable frequency light chopper assembly (Princeton Applied Research, Model 192). Design parameters include compatibility with mount
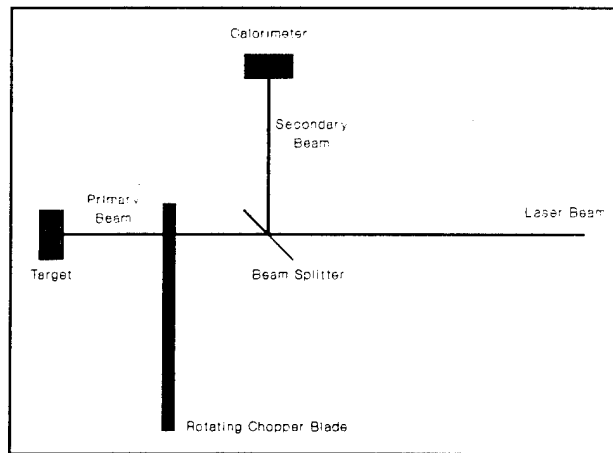
Fig. 1. Location of Chopper Blade After Beam Splitter For the
Production and Measurement of Millisecond Pulses.

dimensions, laser beam diameter, and rotating speed.

The blade mount will accommodate a 4.062 inch radius blade. Beam diameter requires a beam stop and gap dimension of at least 0.75 inch. The chopper assembly operates over a range of 2.5 - 100 volts relating to 2.5 - 100 rps. It is possible to obtain speeds outside this range by applying an external voltage source. The external voltage adds to the assembly voltage. An applied negative voltage will reduce the rps. This is necessary to increase the period of rotation to greater than 0.5 s in order to accommodate calorimeter response time. The low rotational speed, however, implies a low angular momentum, thus causing the stator and rotor of the electric motor to become "unlocked". The blade then ceases to rotate at a constant angular velocity making it difficult to set the necessary combination of blade gap angle and rotating speed for a desired pulse width. This problem can be minimized by balancing the inertia forces of the blade. A balanced blade will also operate with less vibration at high speed.

Chopper Blade Design

The variable angle chopper blade consists of two individual blades, which can be set to create a desired gap angle. In order that the double blade assembly be balanced in any configuration, each blade must be individually balanced.

Static- or single-plane balancing is all that is required in this case because the axial dimension (0.125 inch) of the blade assembly is small compared to the radial dimension. This type of balancing is generally used with fly wheels, gears, etc.

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In order for a moving system to be balanced, all forces acting on the system must sum to zero. Using the method of d'Alembert, Newton's second law is written in the form

$$\sum \boldsymbol{F} - m\boldsymbol{a} = 0. \tag{1}$$

External forces are neglected here because they cannot be balanced by changes in system geometry. Each plate is divided into segments. Each segment is imagined to be a point mass centered at the segment's center of gravity. For a rotating system at constant angular velocity the inertial forces are given by the general expression

$$- m_1 \boldsymbol{R}_1 \omega_1^2 - m_2 \boldsymbol{R}_2 \omega_2^2 - \ldots - m_n \boldsymbol{R}_n \omega_n^2 = 0, \tag{2}$$

where m is the mass of the segment, ω is the angular velocity and **R** is the radial distance to the center of gravity of the segment. The negative sign indicates the force is acting in a direction away from the system pivot. ω is constant in Eq. 2 and can be divided out. The mass is obtained with the expression

$$m = \rho A t, \tag{3}$$

where ρ is the density of the material, A is the area of the segment, and t is the thickness. ρ is constant as is the blade thickness. With these considerations Eq. 2 becomes

$$- \boldsymbol{R}_1 A_1 - \boldsymbol{R}_2 A_2 - \ldots - \boldsymbol{R}_n A_n = 0. \tag{4}$$

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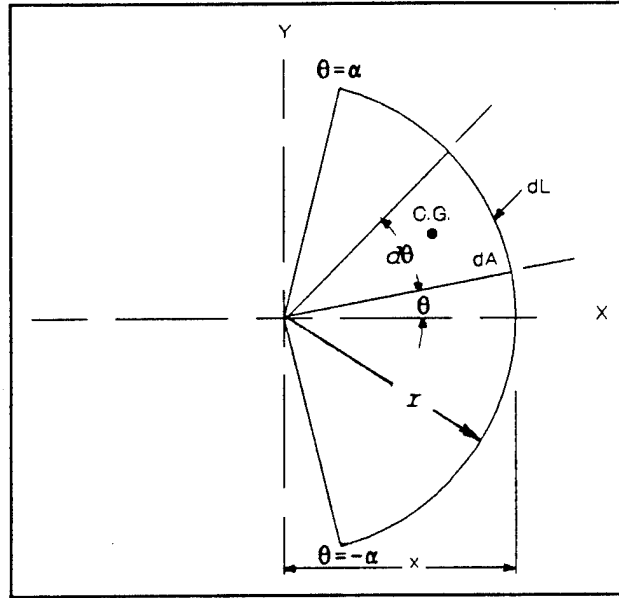
Fig. 2. General Segment Used in Derivation of First Area Moment Expressions.

The product R_nA_n in the previous equation is the first area moment of inertia with respect to some arbitrary axis. We need expressions for both A_n and R_n. Referring to Fig. 2 we can write

$$A = \int_{-\alpha}^{\alpha} dA = \alpha r^2.$$ (5)

The first moment with respect to the y axis can be obtained from the expression

$$Q_y = \int R_{\overline{x}_{el}}\, dA = R_{\overline{x}}\, A,$$ (6)

where $R_{\overline{x}_{el}}$ is the distance along the x axis to the center of gravity of the element and $R_{\overline{x}}$ is the distance to the center of gravity of the entire segment. From Fig. 2 we have

$$dA = \frac{1}{2} r^2\, d\theta,$$ (7)

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$$dL = r \, d\theta, \tag{8}$$

and

$$x = r \cos\theta. \tag{9}$$

In the limit as $\theta \to 0$, the element in Fig. 2 closely approximates a triangle. We can therefore write

$$R_{\overline{x}_{el}} = \frac{2}{3} r \cos\theta. \tag{10}$$

Combining Eqs. 7-10 with Eq. 6 we obtain

$$Q_y = \int_{-\alpha}^{\alpha} \frac{1}{3} r^3 \cos\theta \, d\theta = \frac{2}{3} r^3 \sin\alpha = R_{\overline{x}} A. \tag{11}$$

Combining Eq. 11 with Eq. 5 and solving for $R_{\overline{x}}$, an expression is obtained for the radial distance to the segment's center of gravity as a function of the segment radius and angle

$$R_{\overline{x}} = \frac{2}{3} \frac{r \sin\alpha}{\alpha}. \tag{12}$$

This expression is then used with Eq. 4 to balance each blade.

Assigning an axis through the center of each blade and taking advantage of geometrical symmetry, Eq. 4 was solved with dimensions that conform to the previously stated physical constraints of maximum blade diameter and beam width. Note that holes are created by subtracting and adding appropriate segments. For example, in order to create a 1-inch radial hole that subtends an angle of 30° in a 6-inch radius blade, one would define the first area moment of inertia of a 30° degree segment of radius 6 inches, subtract from it the first area moment of inertia of a 30° segment of radius 5 inches, then add the first area moment of inertia of a 30° segment of radius 4 inches. The final blade designs are shown in Figs. 3 and 4.
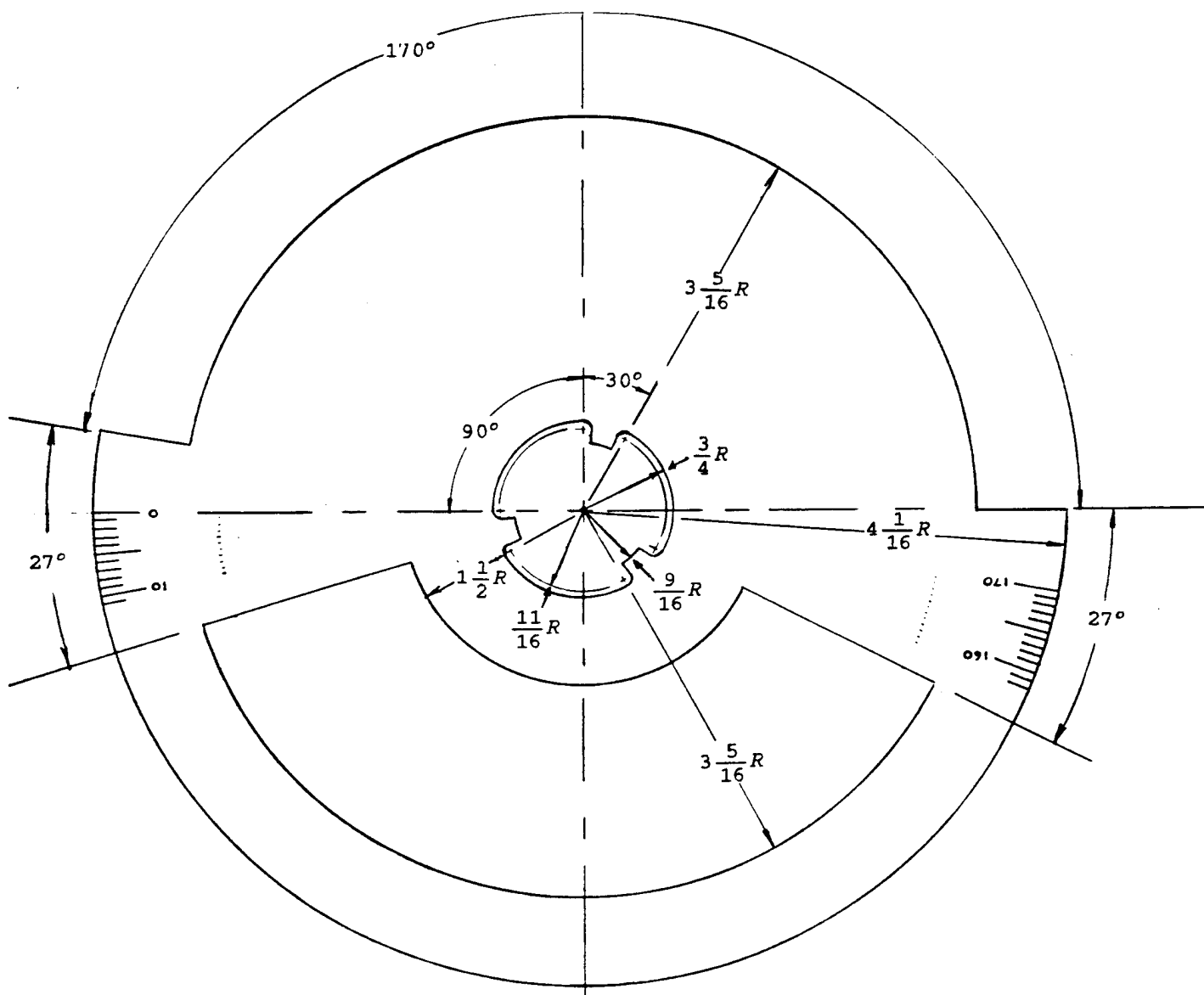
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Fig. 3.   Balanced Chopper Blade Part A.
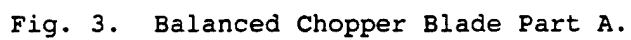
Fig. 4. Balanced Chopper Blade Part B.

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MILLISECOND PULSE GENERATING SYSTEM (MPGS) DEMONSTRATION:
CALORIMETER TEMPORAL RESPONSE

In order to demonstrate the use of the MPGS, a study was performed where a series of pulses ranging from 10 ms to 500 ms were created with the system. The study shows the accuracy that can be obtained in producing pulses in the the millisecond range and quantifies the minimum pulse width necessary to obtain accurate irradiance measurements. It also gives additional relevant information concerning the temporal response of the calorimeters[2] currently being used in our thermal studies.

Experimental Procedure

The experimental setup is identical to that shown in Fig. 1 with the exception that the target is replaced with a second calorimeter. We then have a calorimeter in the secondary beam, which registers the irradiance of the pulse emitted through the water-cooled shutter in the laser head, and a calorimeter in the primary beam, which registers the pulse generated by the rotating chopper blade. By incrementally increasing the pulse length at the primary beam and comparing it to a previously designated ratio of primary to secondary beam, we eventually arrive at the minimum pulse length required to obtain accurate irradiance measurements.
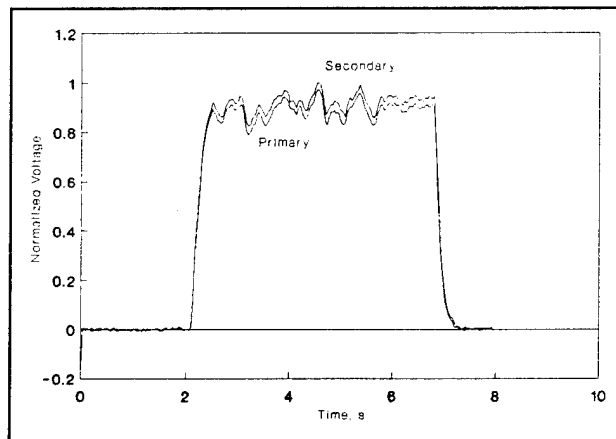

Fig. 5. Normalized Calorimeter Output Voltage Vs Time For a 5 s Pulse.

The average ratio of primary to secondary calorimeter voltage was obtained by recording a 5 s pulse generated by the laser-head shutter. Normalized output voltage vs time for this run is shown in Fig. 5. The ratio is calculated to be 0.96.

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In order to determine the gap angle at which the blade system must be set, a preliminary run is conducted--in this case with the speed control set at 2.5 rps. A photodetector mounted in the assembly produces an alternating 0 to 5 volt output, which is used to determine the actual angular speed. An angular speed of 2.5 rps relates to a period of rotation of 0.4 s. For 10 ms, 50 ms, and 100 ms pulses, the blade gap must be set at 9°, 45°, and 90°, respectively. To create longer pulses with the system, the period of rotation is increased and determined in the same fashion. In this case, for pulses of 200 ms, 300 ms, 400 ms, and 500 ms at the primary beam, a period of rotation of 1.22 s was used, and gap angles were set at 59°, 89°, 118°, and 148°, respectively. These results are summarized in Table 1.

Table 1. Results of Study to Determine Temporal
Characteristics of Calorimeters.

Desired Pulse (ms)	Angular Gap	Period of Rotation (s)	Pulse at Secondary Beam (s)	Actual Period of Rotation (s)	Actual Pulse (ms)	Percent Error
10	9°	0.4	0.5	0.398	9.95	0.5%
50	45°	0.4	0.5	0.397	49.6	0.8%
100	90°	0.4	0.5	0.402	100.5	0.5%
200	59°	1.22	1.3	1.18	193	3.5%
300	89°	1.22	1.3	1.20	296	1.4%
400	118°	1.22	1.3	1.17	382	4.5%
500	148°	1.22	1.3	1.22	502	0.3%

The desired pulse widths shown in column 1 are created by setting the gap of the blade system to an angle (column 2) based on the experimentally predetermined period of rotation given in column 3. The water-cooled laser shutter speed (column 4) is set to a value slightly greater than the period of rotation of the blade and the response time of the calorimeter. Three channels of data were recorded for this experiment; the output voltage of each calorimeter and the photodetector output from which the actual period of rotation (column 5) was determined. If it is assumed that the gap angle can be set with negligible error, then the actual pulse width (column 6) can be determined with the actual period of rotation data. The percent errors given in column 7 compare the desired pulse width to the actual.

RESULTS

Plots were generated for each of the 7 runs documented in Table 1. These
are shown in the Appendix in Figs. A-1 to A-7. In each plot normalized output
voltage is shown for both the primary and secondary calorimeters. These plots
should be compared to Fig. 5. In Fig. A-1 it can be seen that the primary
calorimeter has barely responded to the 10 ms pulse, giving an output voltage
signal which is less than 10% of that which corresponds to the actual
irradiance incident on the calorimeter. For each consecutive run, as the
pulse width at the primary beam is increased, the output voltage of the
primary calorimeter begins to represent more closely that of the actual
irradiance level. At 500 ms (Fig. A-7) the primary calorimeter just begins to
give accurate readings approaching the ratio shown in Fig. 5, and confirming
the manufacturer's stated response time of 0.5 s.

Clearly, the greater the pulse width at the secondary calorimeter, the
greater the accuracy of the irradiance measurement. The general pulse shape
is shown in Fig. 6. The ramp up and ramp down portions of the pulse are due
to a combination of 1) the time required for the shutter to open and close and
2) the response time of the calorimeter. In a similar study[3] it was
determined that the most accurate readings can be obtained by averaging over
that portion of the pulse beginning at point C that is generally well defined
and counting back to point B, which is 0.5 s into the pulse; this eliminates
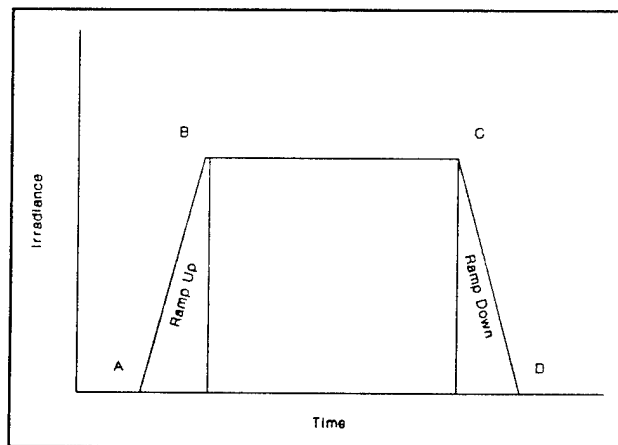the ramp up and ramp down portions of the pulse profile.

Fig. 6. General Profile of Laser Pulse Created by Water-Cooled
Shutter in Laser Head.

CONCLUSIONS AND RECOMMENDATIONS

A new millisecond pulse generating system has been developed, constructed, and implemented using a set of chopper blades fabricated at Natick and additional equipment currently available in our laboratory. Design considerations were summarized and expressions were derived that were used in the design of a balanced chopper blade system capable of creating single pulses or pulse trains in the millisecond range. System accuracy was investigated and found to be acceptable for our purposes. Errors of less than 5% were demonstrated in achieving a desired pulse width and negligible errors (< 0.5%) were encountered in determining the actual pulse width when a high sampling rate (~1000 Hz) was used in data acquisition.

In addition, the temporal characteristics of the calorimeters that we are currently using were investigated. A 0.5 s calorimeter response time was determined and the proper irradiance measurement technique was discussed.

Future work should be directed at determining the possible combinations of pulse widths and periods which can be obtained with the system when it is used to create pulse trains. The incorporation of pulse trains into our standard fabric testing procedures should be considered as well as the use of the system in industrial applications.

The millisecond pulse generating system has performed as designed and will significantly extend our capabilities in the area of thermal testing.

REFERENCES

1. Laboratory Notebook #9114, U.S. Army Natick Research, Development and Engineering Center, September 30, 1993, pp. 133-4.

2. Hy-Cal Engineering, 12105 Los Nietos Road, Santa Fe Springs, California, model C-1112-B-60-120.

3. Laboratory Notebook #9114, U.S. Army Natick Research, Development and Engineering Center, March 19, 1993, pp. 63-8.
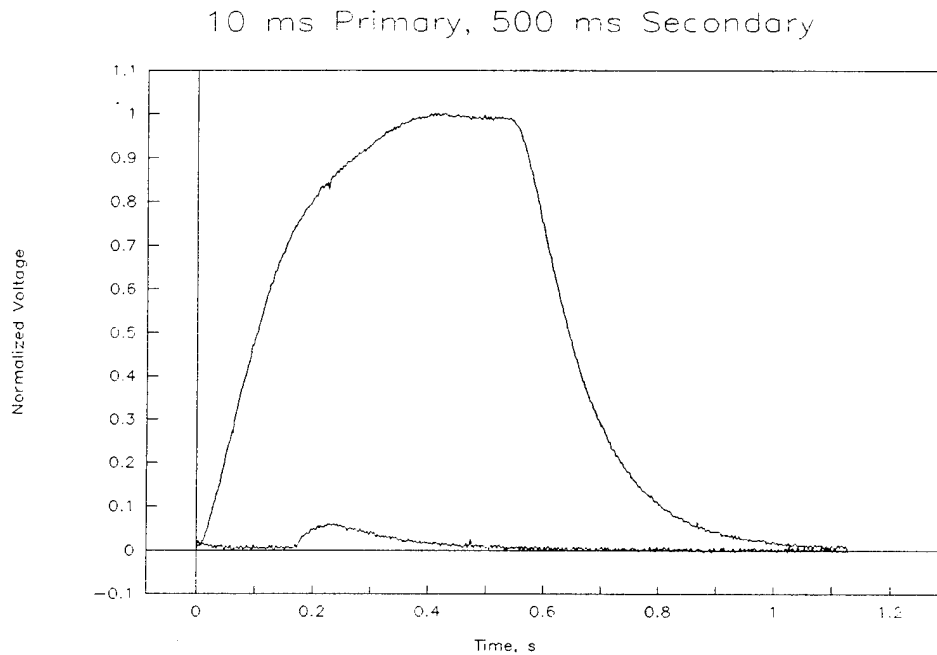
APPENDIX

Calorimeter Temporal Response Curves

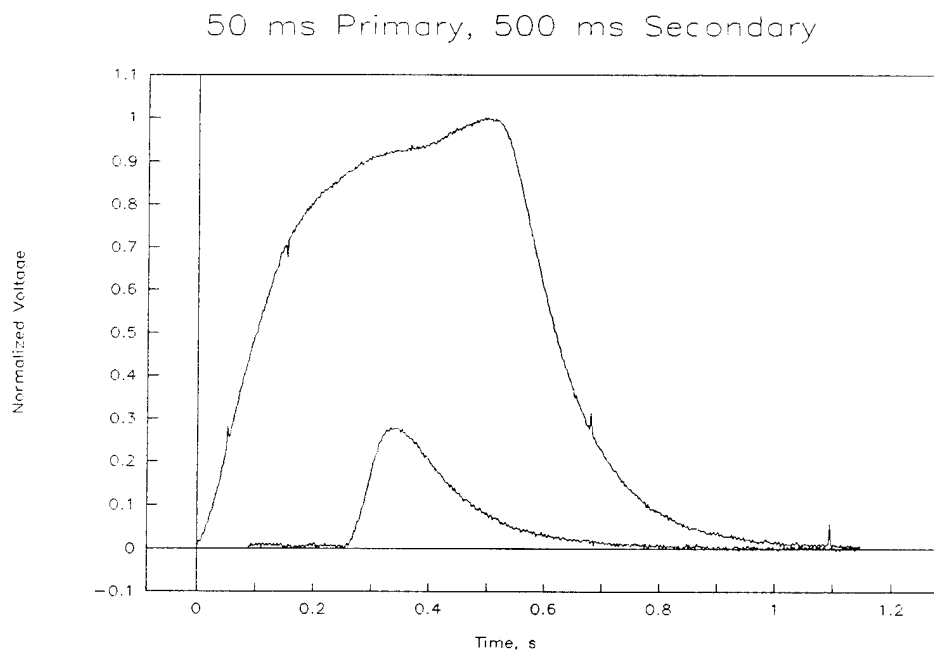**Fig. A-1.** Normalized Voltage Versus Time For 10 ms Primary Pulse and 500 ms Secondary Pulse.

Fig. A-2. Normalized Voltage vs Time For 50 ms Primary Pulse and 500 ms Secondary Pulse.
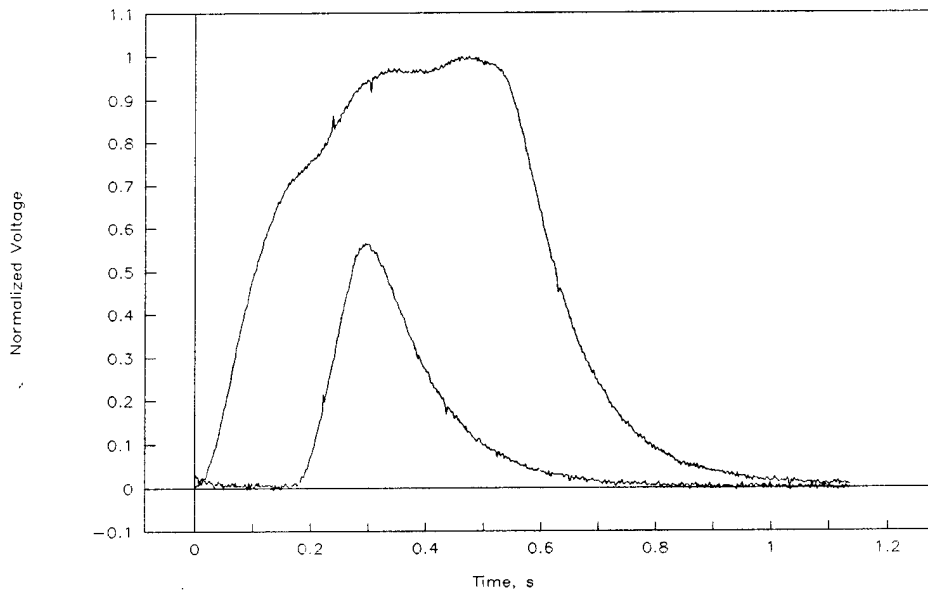
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100 ms Primary, 500 ms Secondary

Fig. A-3. Normalized Voltage vs Time For a 100 ms Primary Pulse and 500 ms Secondary Pulse.

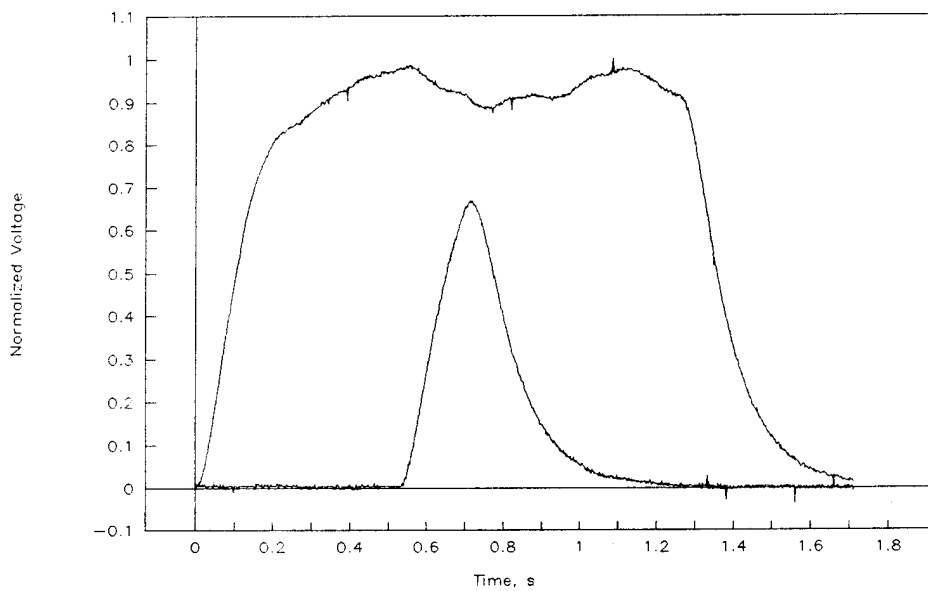## 200 ms Primary, 1.30 s Secondary

Fig. A-4. Normalized Voltage Vs Time For a 200 ms Primary Pulse and 1.30 s Secondary Pulse.
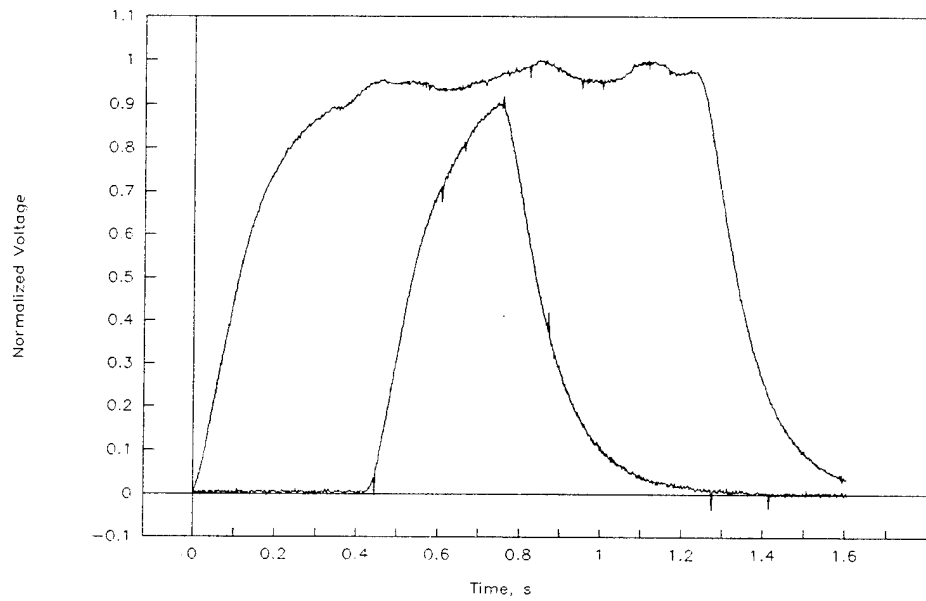
300 ms Primary, 1.30 s Secondary

Fig. A-5. Normalized Voltage vs Time For 300 ms Primary Pulse and
and 1.30 s Secondary Pulse.

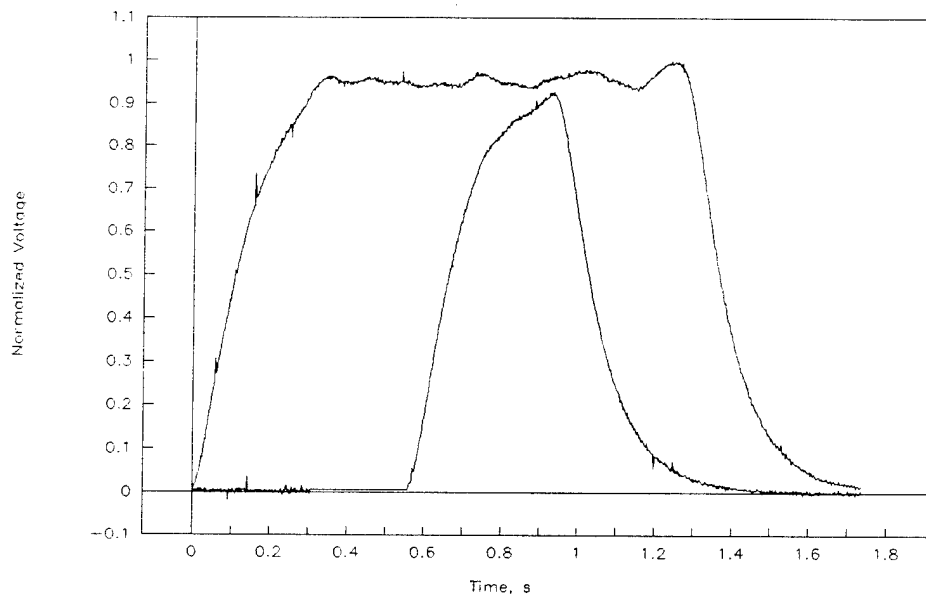**400 ms Primary, 1.30 s Secondary**

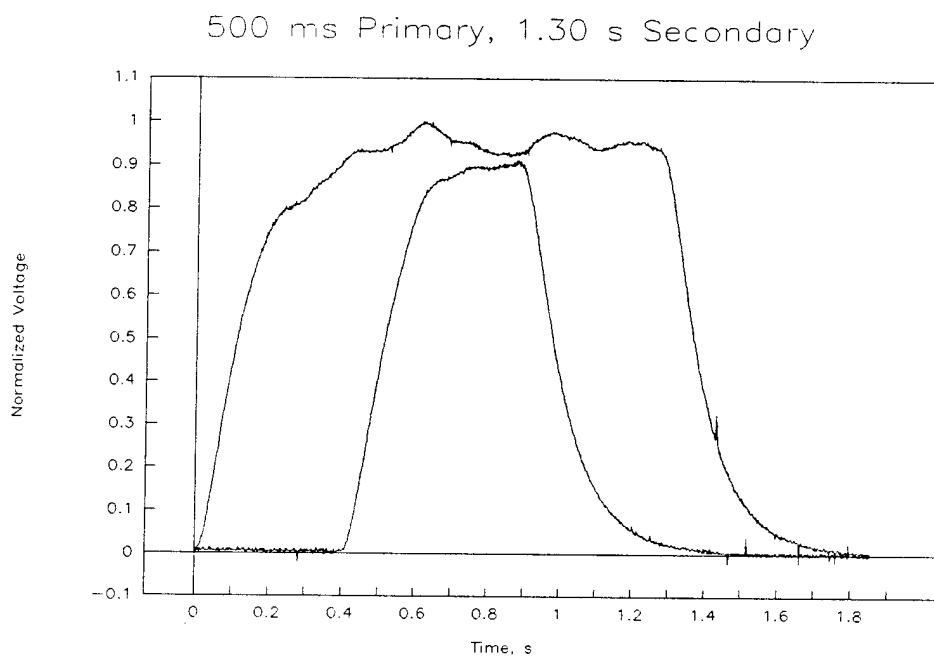Fig. A-6. Normalized Voltage Vs Time For 400 ms Primary Pulse
and 1.30 s Secondary Pulse.

Fig. A-7.   Normalized Voltage Vs Time For 500 ms Primary Pulse
and 1.30 s Secondary Pulse.

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